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Numerical simulation of a turbulent wake subjected to adverse pressure gradient

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Abstract. Results are presented of high-fidelity scale-resolving simulations of the wake flow exposed to adverse pressure gradient (APG). Specifically, zonal RANS-IDDES computations are performed of the flow model designed and manufactured at the Technische Universität Braunschweig in the framework of a joint German-Russian project "Wake in Adverse Pressure gradient". The model includes a flat plate as the wake generator and two pairs of thin liner foils creating APG. Results of the computations of mean flow characteristics agree with currently available experimental data and differ from those of the RANS predictions. This suggests the necessity of RANS models improvement which is planned to be done with the use of the combined experimental/numerical database on the mean flow and turbulence statistics of the wake accumulated in the course of the project.

1. Introduction

Design and optimization process of the high-lift wings of modern commercial airplanes involves numerous multi-variant CFD computations. As of today, at practically meaningful (high) Reynolds numbers, the only affordable modeling framework for such computations is the Reynolds Averaged Navier-Stokes (RANS) equations combined with semi-empirical turbulence model. However, as shown in a number of studies of the wakes subjected to a strong APG, which is a common underlying flow feature of the high-lift wings near the maximum lift (during the take-off and landing), reliability of the RANS-based prediction of this class of flows has not yet been achieved (see, e.g. [1, 2]). This motivated a joint German-Russian project "Wake flows in Adverse Pressure Gradient" launched in 2017. The project presumes conducting of both a detailed experimental study and high-fidelity Scale-Resolving Simulations (SRS) of the wake subjected to APG and, ultimately, developing of corresponding improved RANS model(s).

The present paper outlines first results of the SRS (zonal RANS-IDDES) computations of the experimental flow model designed and manufactured in the course of the project at the Technische Universität Braunschweig (TU BS). It is organized as follows.

In Section 2, a brief description of the experimental setup is presented. Then, in Section 3, some details are given of the computational problem statement and numerical aspects of the computations performed. After that, in Section 4, results of the computations are presented and discussed. Finally, in Section 5 some conclusions based on the performed studies are drawn.

2. Model flow description

Figure 1 shows a sketch of the experimental flow model designed by TU BS. Its detailed description along with an outline of the experimental setup is presented in [3]. The model includes a flat plate (FP) as a wake generator and two pairs of symmetrically installed liner foils (LF1 and LF2) creating APG. All the elements of the model are mounted between the wind tunnel sidewalls. In order to prevent separation of the wake-flow from these walls observed in the initial experiments [3] (this is essential for ensuring two-dimensionality of the mean flow), thin splitter plates are installed parallel and close to the sidewalls between the upper (LF1.1 and LF2.1) and lower (LF1.2 and LF2.2) liner foils. The level of the created APG may be controlled by varying the distance of the upper and lower liner foils to the center plane of the test section.

In the experiments the free stream velocity U_0 is varied from 24m/s to 48m/s. This corresponds to the variation of the Reynolds number based on the plate length L = 1.058 m and U_0 from 1.6 to 3.2 million. Corresponding Mach number is less than 0.1, which justifies using the incompressible flow assumption in the simulations.

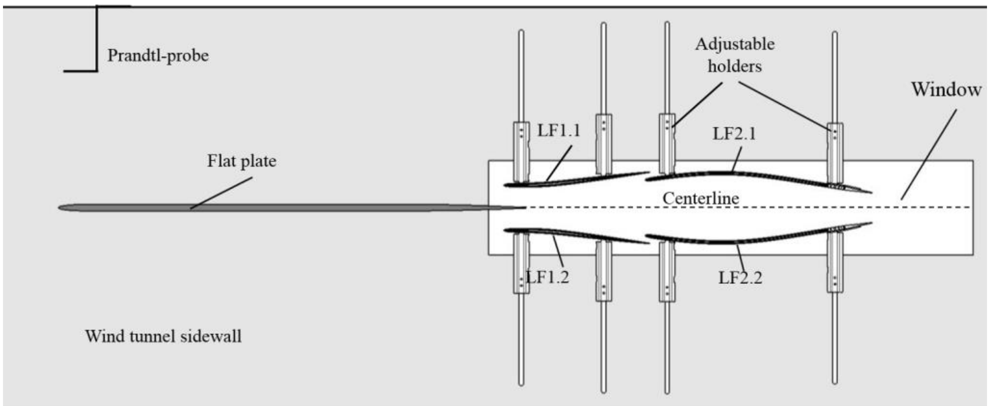

Figure 1. Sketch of experimental flow model installed in TU BS wind tunnel

3. Computational problem setup and numerical aspects of the computations

A computational domain and grid in *XY*-plane used in the simulations are shown in Figure 2.

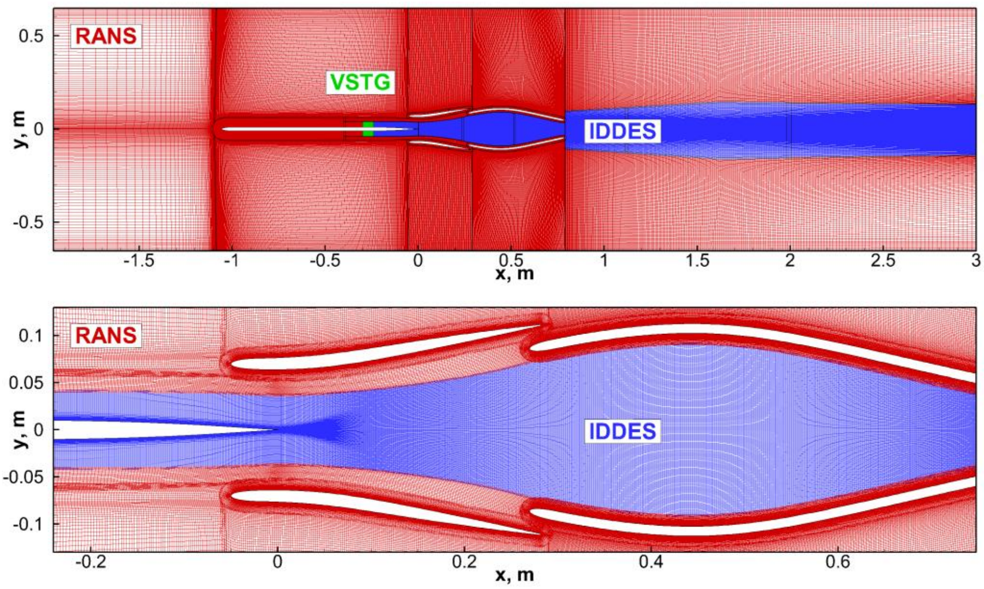

Figure 2. Computational domain, grid, and RANS & IDDES sub-domains in *XY*-plane. Upper frame: full domain; lower frame: zoomed in wake region

As seen in this figure, the entire computational domain is subdivided into two sub-domains (zones), RANS and IDDES ones. In the RANS zone the *k*-ω RANS model of Menter [4] is applied, whereas in the IDDES zone we use the IDDES approach [5] with the same underlying RANS model. The RANS zone extends from the inlet boundary of the domain to the section x = -0.3m and also includes the outer part of computational domain at larger x and boundary layers forming on the liner foils. The IDDES zone covers the rest (downstream) part of the FP boundary layer and the wake, which is the focus region in this study. For triggering a rapid transition from RANS to IDDES, the Volume Synthetic Turbulence Generator (VSTG) [6, 7] was used at the RANS-IDDES interface. Hence, in the downstream part of the attached FP boundary layer the IDDES performs as Wall Modeled LES (WMLES) and in the wake it functions as a pure LES [5].

The boundary conditions used in the simulations were as follows.

On the FP and LF surfaces no-slip conditions were applied. At the inflow a uniform profiles of all the flow quantities except for the pressure were specified, and at the outflow boundary a constant pressure was imposed. The upper and lower boundaries (test section "ceiling" and "floor") were treated as the slip walls, and in the spanwise direction periodic boundary condition were imposed, which assumes the 2D mean flow character in the experiment. The span size of the domain was set equal to 0.1m (this was found to be sufficient to ensure span-size independent statistical flow characteristics).

The computational grid simulations were performed on is a structured Chimera-type grid containing 22 overlapping blocks with around 30M cells total. The grid is clustered near the FP and liner foils walls so that the size of the first near wall step in the wall-normal direction would be less than 1.0 in wall units. In the IDDES sub-domain the grid steps in the streamwise and spanwise directions, Δx and Δz, are equal to $2\cdot10^{-3}$m and 10^{-3}m, respectively, which corresponds to $\Delta x/\delta = 0.15$, $\Delta z/\delta = 0.075$ (δ is the thickness of the boundary layer in the vicinity of the FP trailing edge). These steps were proven to be sufficiently small for obtaining nearly grid-independent solution [8].

The computations were performed with the use of the in-house code of the Saint-Petersburg Polytechnic University "Numerical Turbulence Simulation" (NTS code) [9]. This is a cell-vertex finite-volume code accepting structured multi-block overset grids of the Chimera type. The incompressible branch of the code used in present simulations employs the flux-difference splitting method of Rogers and Kwak [10]. In the RANS sub-domain the inviscid fluxes in the governing equations are approximated with the use of a 3rd-order upwind-biased scheme and in the IDDES sub-domain a 4th-order central scheme is used. The viscous fluxes are approximated with the 2nd-order central scheme. For the time integration, an implicit 2nd-order backward Euler scheme with sub-iterations is applied. The time step Δt was chosen to ensure less than 1.0 Courant number.

4. Results and Discussion

Some key results of the simulation performed at Re = $3.2\cdot10^{6}$ are shown in Figures 3-8.

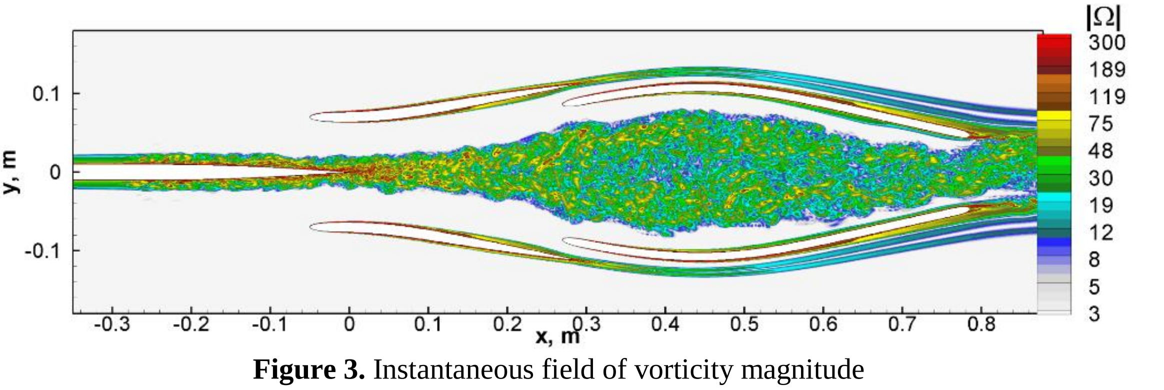

Figure 3. Instantaneous field of vorticity magnitude

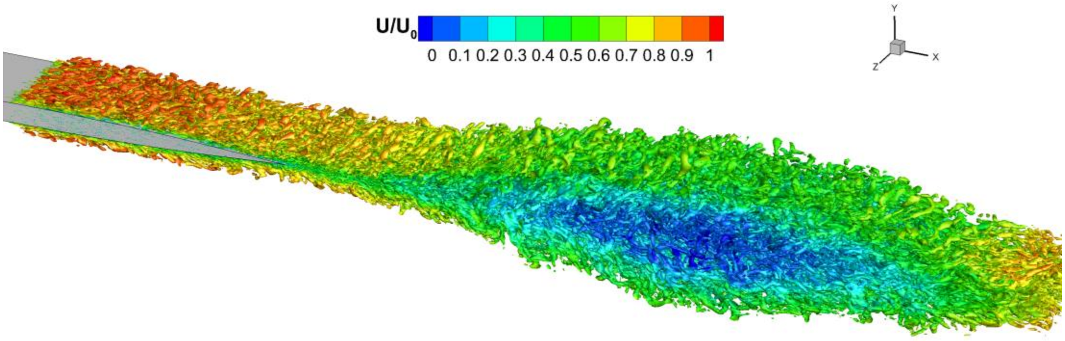

Figure 4. Isosurface of Q-criterion colored by streamwise velocity

In particular, Figures 3-4 present flow visualizations in the form of instantaneous field of the vorticity magnitude in an *XY*-plane and an isosurface of the Q-criterion colored by streamwise velocity. The figures visibly display fine (consistent with the grid used) resolved turbulent structures in the IDDES sub-domain (both in the attached FP boundary layer and in the wake), thus suggesting a plausible functionality of the VSTG and IDDES in the WMLES and LES modes. Other than that, the flow visualizations clearly reveal presence of an extended stagnation region in the wake, which is a peculiar feature of the wakes subjected to APG.

Figures 5 – 7 compare mean and statistical characteristics of the considered flow predicted by the RANS-IDDES with those computed with the use of 2D steady RANS with two turbulence models, the k-ω SST model and explicit algebraic Reynolds stress model [11] based on the BSL k-ω model [4]. Analysis of these figures suggests that both RANS models considerably overestimate the minimum velocity in the stagnated area of the wake and under-predict velocity in its initial region.

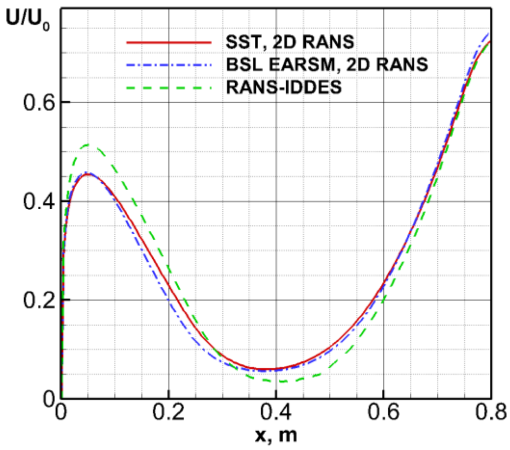

Figure 5. Comparison of mean velocity distribution along the wake symmetry line $y = 0$ predicted by RANS-IDDES and by SST and BSL EARSM RANS models

Moreover, as seen in Figures 6 and 7, both considered RANS models fail to reproduce the evolution of the profiles of the turbulent kinetic energy k and its viscous dissipation rate ε predicted by the RANS-IDDES (note that in the framework of RANS-IDDES, the viscous dissipation rate was computed from the budget of the k-transport equation as proposed by Dejoan and Leschziner [12]). Namely, they tend to significantly over-predict the kinetic energy in major part of the wake, thus driving an overproduction of dissipation rate through the ε-production term.

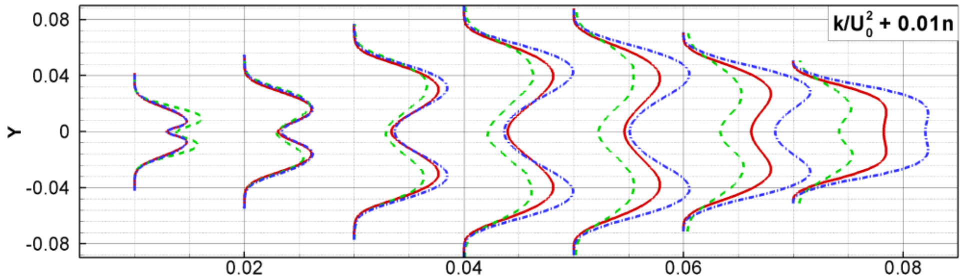

Figure 6. Comparison of profiles of turbulent kinetic energy in different wake sections $x_n = (0.1n)$ m, $n = 1, 2,\ldots,7$ predicted by RANS-IDDES and by SST and BSL EARSM RANS models (see Figure 5 for the legend)

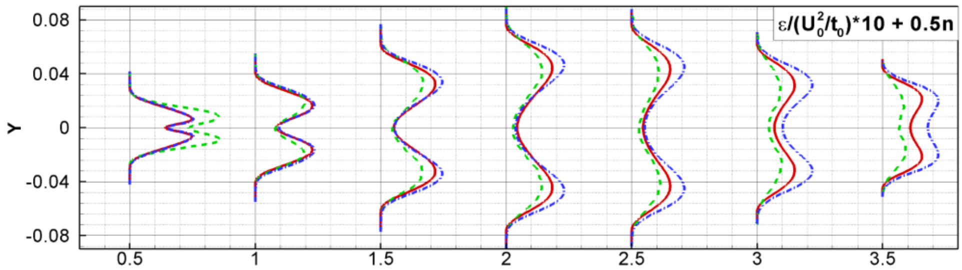

Figure 7. Comparison of profiles of viscous dissipation rate in different wake sections $x_n = (0.1\text{n})$ m, n = 1, 2,…7 predicted by RANS-IDDES and by SST and BSL EARSM RANS models (see Figure 5 for the legend)

Finally, Figure 8 presents a comparison of the RANS-IDDES prediction of the static pressure distribution over the FP and liner foil surfaces with the corresponding distributions measured in the experiments (these are the only currently available experimental data [3]). It demonstrates a good agreement, which supports adequacy of the computational RANS-IDDES approach and the entire computational setup for the flow in question.

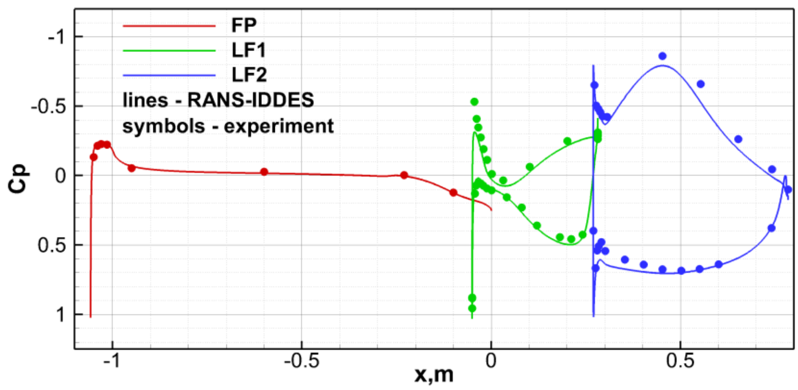

Figure 8. Comparison of mean pressure distributions over FP, LF1 and LF2 predicted by RANS-IDDES and measured in the experiment

5. Conclusions and outlook

First results are presented of zonal RANS-IDDES of the flat plate wake subjected to adverse pressure gradient created by two pairs of thin liner foils at the conditions corresponding to experiments conducted at the Institute of Fluid Mechanics of the Technische Universität Braunschweig. A comparison of the RANS-IDDES prediction with the only currently available experimental data (distribution of the pressure coefficient along the flat plate and liner foils) shows a good agreement. At the same time, a comparison of the results of RANS-IDDES computations with those obtained with the use of two RANS turbulence models (k-ω SST and BSL EARSM) demonstrates that the latter are not capable of accurate predicting either the mean or statistical characteristics of the considered flow. This confirms the expectation that there is a severe need in a further improvement of RANS-based modeling approach to make it a reliable tool for prediction of wakes subjected to strong APG. This objective can be reached based on the results of the RANS-IDDES briefly presented in this paper along with the detailed experimental measurements of the flow in question with the use of the standard and stereo-PIV methodologies, hotwire anemometry, and oil flow visualizations, which are currently being conducted in the framework of the common German-Russian project “Wake in Adverse Pressure Gradient”.

Acknowledgements

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